AFRL-OSR-VA-TR-2013-0596

IMAGING THROUGH TURBULENT MEDIA BASED ON PHASE CONJUGATION IN RESONANTLY - ENHANCED SECOND-ORDER NONLINEAR MATERIALS - A NOVEL SCHEME

YUJIE DING

LEHIGH UNIVERSITY

11/06/2013
Final Report

DISTRIBUTION A: Distribution approved for public release.

AIR FORCE RESEARCH LABORATORY
AF OFFICE OF SCIENTIFIC RESEARCH (AFOSR)/RSE
ARLINGTON, VIRGINIA 22203
AIR FORCE MATERIEL COMMAND

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10/31/2013

2. REPORT TYPE
Final Performance Report

3. DATES COVERED *(From - To)*
August 1, 2010 – July 31, 2013

4. TITLE AND SUBTITLE
Imaging through Turbulent Media Based on Phase Conjugation in Resonantly-Enhanced Second-Order Nonlinear Materials: A Novel Scheme

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-10-1-0414

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Dr. Yujie J. Ding

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering
Lehigh University
19 Memorial Drive West
Bethlehem, PA 18015

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Suite 325, Room 3112
875 Randolph Street
Arlington, VA 22203-1768

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A - Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
During the funding period, we have made a significant progress towards the objectives being set on a class of the important research projects. The major accomplishments include:
* Theory of phase conjugation based on second-order nonlinear parametric processes under a novel configuration
* Generation of phase-conjugated beam based on second-order nonlinear parametric processes, supporting our theory
* Demonstration of phase conjugation that is insensitive to polarization of the input beam
* Achievement of broadband phase conjugation
* Restoration of blurred images due to phase distortion, supporting out theory
* Demonstration of image restoration which is insensitive to the polarization direction and wavelength of the input beam.
As a result of our extensive research, we have made paramount contributions to the long-term mission of the U.S. Air Force. In particular, our results on the restoration of the images will enable us to remove the effects caused by the atmospheric turbulence. Therefore, we will greatly improve the sensitivities and resolutions for imaging and free-space communications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Yujie J. Ding
U	U	U	UU	21	19b. TELEPHONE NUMBER *(include area code)* (610) 758-4582

Final Report on
AFOSR Grant FA9550-10-1-0414

Imaging through Turbulent Media Based on Phase Conjugation in Resonantly-Enhanced Second-Order Nonlinear Materials: A Novel Scheme

Period of August 1, 2010 – July 31, 2013

Program Manager: Dr. Kent Miller

Principal Investigator: Dr. Yujie J. Ding

Professor of Electrical Engineering

Department of Electrical and Computer Engineering
Lehigh University
19 Memorial Drive West
Bethlehem, PA 18015

Phone: (610) 758-4582

Fax: (610) 758-6279

Email: yud2@lehigh.edu

October 31, 2013

Status of effort

During the funding period, we have made a significant progress towards the objectives being set on a class of the important research projects. The major accomplishments include:

- Theory of phase conjugation based on second-order nonlinear parametric processes under a novel configuration
- Generation of phase-conjugated beam based on second-order nonlinear parametric processes, supporting our theory
- Demonstration of phase conjugation that is insensitive to polarization of the input beam
- Achievement of broadband phase conjugation
- Restoration of blurred images due to phase distortion, supporting out theory
- Demonstration of image restoration which is insensitive to the polarization direction and wavelength of the input beam.

As a result of our extensive research, we have made paramount contributions to the long-term mission of the U.S. Air Force. In particular, our results on the restoration of the images will enable us to remove the effects caused by the atmospheric turbulence. Therefore, we will greatly improve the sensitivities and resolutions for imaging and free-space communications.

Accomplishments/New Findings

In the separate sections below, we summarize our accomplishments on these projects mentioned above:

1. **Polarization-Insensitive Optical Phase Conjugation Based on Adhesive-Free-Bonded Periodically-Inverted $KTiOPO_4$ Plates**

Based on adhesive-free-bonded periodically-inverted KTP plates, we have generated a phase-conjugated beam that is insensitive to polarization of the input beam. Such a process can be used to correct a blurred image caused by turbulence.

Optical phase conjugation is one of the most effective nonlinear optical processes for restoring the image blurred by a turbulent medium such as atmosphere. In the past, phase-conjugation devices implemented based on photorefractive effect have response times in the range of 100 μs – 1 s [1], which are extremely slow. Four-wave mixing in a third-order nonlinear medium can also be used to achieve optical phase conjugation [2]. Such a scheme requires two pump beams. Since third-order nonlinearity is weak, the pump powers must be extremely high in order to achieve a reasonably high nonlinear power reflection coefficient. Recently [3], we proposed to achieve phase conjugation based on a backward second-order nonlinear parametric process. The pump power required to achieve a nonlinear power reflection coefficient of 100% can be as low as 1 mW [3].

In order to achieve sufficiently high nonlinear power reflection coefficient based on a second-order nonlinear process, a phase-matching condition must be satisfied. This could be achieved through either birefringence-based phase-matching or quasi-phase-matching (QPM). However, in both cases, the polarization directions of the pump, input and generated phase conjugated beams are selected by the dominant nonlinear coefficient. Namely, only the beam in one particular polarizations for the input and phase-conjugated beams can be phase-matched. However, in order to correct the blurred image, phase conjugation should be independent of the polarization of the input beam. One may argue that at the degenerate point, since the input and phase-conjugated beams have orthogonal polarizations, phase conjugation is independent of the polarization of the input beam. However, the geometric reflection of the input beam demands that the nonlinear power reflection coefficient must be sufficiently high.

Here, we report our result following the implementation of a novel approach for the generation of a phase-conjugated beam based on a second-order nonlinear parametric process. The uniqueness of our scheme lies in the fact that it is insensitive to the polarization of the input beam. In addition, since the wavelength for the phase-conjugated beam is slightly different from that of the corresponding input beam, we can easily separate the conjugated beam from the geometric reflection of the input beam. Therefore, even with a low nonlinear power reflection coefficient, such a scheme can be still used for the correction of a blurred imaging. All these advantages are made possible by exploiting a pair of the orthogonally-polarized signal beams and a pair of the orthogonally-polarized phase-conjugated idler beams generated by periodically-

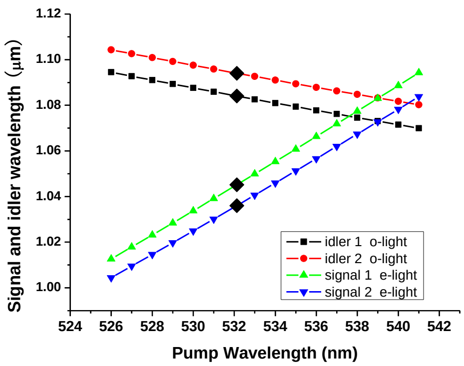

Fig. 1. Signal and idler wavelengths generated from AFB-KTP plates.

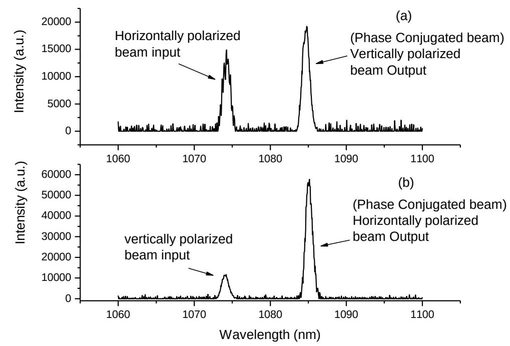

Fig. 2. Polarization-insensitive generation of phase conjugated beam.

inverted $KTiOPO_4$ (KTP) plates which were bonded together by the adhesive-free-bonded (AFB) technique.

A composite KTP stack has 20 pieces of x-cut KTP plates with the cutting angles of θ = 90º and φ = 0º, indicating that each plate is non-critically phase-matched. As the 20 plates were cut from the same bulk KTP crystal, the crystal axes of these plates are aligned to the same directions initially. Before forming the stack, the crystal axes of every other plate are inverted such that the corresponding elements of the second-order nonlinear susceptibility tensor of KTP are all inverted. Such periodic modulations result in a QPM condition [4], i.e. $\Delta k l = \pm\pi$, where Δk is the wave-vector mismatch for each nonlinear parametric process and l is the thickness of each KTP plate. As a result, for each pump wavelength, there is a pair of the signals as well as a pair of the idlers that satisfy the condition above. Each KTP plate has a thickness of 1.19 mm ± 0.01 mm. When the pump wavelength is set to 532 nm, the wavelengths for the pair of the signals are 1034.8 nm and 1044.2 nm (ordinary wave - *o*) whereas those for the pair of the idlers are 1084.1 nm and 1093.9 nm (extraordinary wave - *e*), respectively, as shown in Fig. 1 [5]. As the pump wavelength is increased to 539 nm, the two nonlinear parametric processes reach the degenerate point. However, the wavelengths of the signal and idler are different, i.e. the wavelengths for the first pair of signal and idler are 1073 nm (e) and 1083nm (*o*) whereas the wavelengths for the second pair are 1083 nm (*e*) and 1073 nm (*o*), respectively. In contrast, at the degenerate point in a bulk KTP crystal, the signal and idler have exactly the same wavelength of 1078 nm.

The generation of two pairs of the orthogonally-polarized signals and idlers can be exploited for generating the polarization-insensitive phase-conjugated beams. Indeed, assuming that the input beam at 1073 nm has both horizontal and vertical polarization components, the phase-conjugated beams for these two corresponding polarizations can be simultaneously generated by mixing them with the pump beam at 539 nm. Indeed, we mixed the pump beam at 539 nm with the input beam at 1073 nm, polarized in a horizontal or a vertical direction. Fig. 2(a) shows the spectrum for the horizontally-polarized input beam at 1073 nm after mixing it with the pump beam. A phase-conjugated beam in the vertical direction was observed at 1083 nm. Similarly, when we mixed the input beam at 1073 nm, polarized in the vertical direction, with the pump beam, the phase-conjugated beam at 1083 nm was observed, which was horizontally polarized, see Fig. 2(b).

In order to demonstrate the restoration of an image being blurred by a turbulent medium based on phase conjugation, we assembled a setup based on the nonlinear parametric processes in the AFB KTP plates, see Fig. 3. The pump beam at 539 nm is an output generated by a MOPO system (10 Hz, 5 ns). In order to generate the input beam for the phase conjugation, we set up an optical parametric oscillator (OPO) based on a bulk KTP crystal. The signal of such an OPO was then used as an input beam and mixed with the pump beam at 539 nm inside the AFB-KTP stack. To simulate a blurred image, a phase-distorting plate was inserted into the optical path. To recover the image from such distortion, the phase-conjugated beam was then reflected back along the previous path by a mirror and it subsequently propagated through the distorting plate at the same spatial location. A CCD camera was used to capture the image being generated by the phase-conjugated and residual input beams, respectively, by switching between the two positions #1 and #2. Correspondingly, the image being captured from position #1 has a significantly-improved image quality compared with that being captured at position #2, see Figs. 4(a) and 4(b).

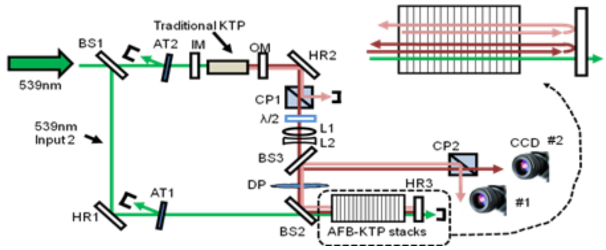

Fig. 3. Experimental setup for the image recovery.

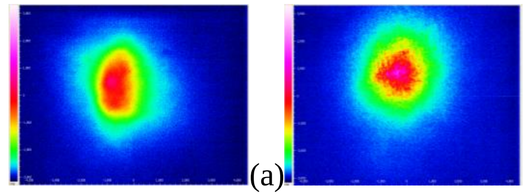
(a) (b)

Fig. 4. (a) Residual input beam image; (b) phase conjugated beam image.

References to Section 1

[1] P. Yeh, "Fundamental limit of the speed of photorefractive effect and its impact on device applications and material research," Appl. Opt. **26**, 602-604 (1987).

[2] For a review, see various chapters in R. A. Fisher, ed., *Optical phase conjugation*, Academic, NY, 1983.

[3] Y. J. Ding, "Phase conjugation based on single backward second-order nonlinear parametric process," Opt. Lett. **37**, 4792-4794 (2012).

[4] X. Mu, H. Meissner, and H. C. Lee, "Optical parametric oscillations of 2 μm in multiple-layer bonded walk-off compensated KTP stacks," Opt. Lett. **35**, 387-389 (2010).

[5] P. Zhao, S. Ragam, Y. J. Ding, I. B. Zotova, X. Mu, H.-C. Lee, S. K. Meissner, and H. Meissner, "Singly resonant optical parametric oscillator based on adhesive-free-bonded periodically inverted KTiOPO4 plates: terahertz generation by mixing a pair of idler waves," Opt. Lett. **37**, 1283-1285 (2012).

2. Restoration of Blurred Images Due to Phase Distortion Based on Polarization-Insensitive Phase Conjugation in Second-Order Nonlinear Medium

Broadband and polarization-insensitive phase conjugation, achieved based on difference-frequency generation in a second-order nonlinear composite consisting of stacked KTP plates, was exploited to restore blurred images due to phase distortion as a novel scheme. Due to the quasi-phase matching in the stacked KTP crystals, our result reveals that the image restoration is insensitive to the polarization direction and wavelength of the input beam.

Restoration or correction of blurred images caused by scattering and phase-distortion medium is important in many applications from defense to astronomy [1-3]. Optical phase conjugation (OPC) is capable of eliminating the phase distortion caused by a distortion medium [4]. However, when such a distortion is caused by atmospheric turbulence, OPC has not become a practical solution for image corrections yet. Indeed, OPC based on photorefractive effect has typical response times of (1 ms -1 s) [5], which cannot be used to correct the distorted images caused by the dynamic atmospheric turbulence. On the other hand, four-wave mixing in a third-order nonlinear medium can be used to achieve OPC.

However, the pump powers required are too high for any practical applications [5]. Recently [6], we proposed to achieve phase conjugation based on a single backward second-order nonlinear parametric process. Since the second-order nonlinear coefficient can be much higher than the third-order counterpart, our calculation shows that a nonlinear power reflection coefficient of close to 100% is achievable using a pump power of ~1 mW, which can be achieved by a low-power diode laser. OPC based on a second-order nonlinear parametric process overcomes the disadvantages of slow response based on photorefractive effect and requirement of high pump powers based on four-wave mixing. Therefore, such a second-order nonlinear process is ideal for corrections of the blurred images after going through the atmospheric turbulence. However, all of the schemes based on nonlinear processes in the past suffer from a major drawback, i.e. OPC works only for a specific polarization and wavelength of the input beam [7-9].

In the previous work, we demonstrated that for a fixed pump wavelength, two sets of signals and idlers can be simultaneously generated from a nonlinear composite consisting of adhesive-free-bonded (AFB) periodically-inverted $KTiOPO_4$ (KTP) plates [10,11]. Due to the presence of the signals and idlers having perpendicular polarizations, such a nonlinear process is insensitive to the polarization of the input beam. In the past, theoretical and experimental studies of three-wave interaction had been investigated in different nonlinear crystals, such as theoretical study of difference-frequency generation (DFG) in β-BaB_2O_4 (BBO) for different angles between the input and pump beams [12], experimental and simulation work on the quality of phase conjugate affected by the flatness of pump wave front [13], and phase conjugated beams generated by a transversely pump beam [14,15]. However, all of them suffer from a major disadvantage, i.e. the nonlinear process is sensitive to the polarizations of the waves participating in the nonlinear interactions.

Physical idea of the image restoration is to remove the phase distortion caused by an aberrant medium. A plane wave passes through a disturbing medium suffers from phase aberration of $\varphi(x, y, z)$, such phase aberration will accumulate and become doubled to be $2\varphi(x, y, z)$ when the wave is reflected from a mirror and passes the disturbing medium again in return. However, the phase aberration can be totally removed, and therefore, the original phase of the input plane wave recovers if a phase conjugate mirror is used instead of an ordinary mirror. The detailed mathematical formulation can be found in Ref. [5].

Here, we report our most recent results following our demonstration of restoration of the phase-distorted images based on DFG in AFB-KTP plates. We have demonstrated that corrections of blurred images are insensitive to the polarization of the input beam, which is considered as the advance of the field compared with the previous result [7]. To the best of knowledge, this is the first demonstration of polarization-insensitive restoration of the images. In addition, we have also demonstrated that such a method is effective even when the wavelengths of the input and phase-conjugated are different from each other.

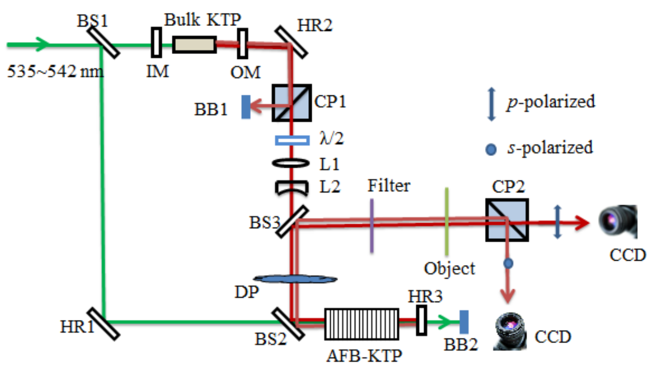

Fig. 1. (Color online) Experimental setup for imaging based on phase conjugation. BS1-3: Beam splitter; HR1-3: high reflection mirror; IM: input mirror; OM: output mirror; BB1-2: beam block; L1-2: convex and concave lens; CP1-2: cubic polarizer; λ/2: half-wave plate; DP: distortion plate; CCD: CCD camera.

The nonlinear composite used in the parametric interaction consists of 20 pieces of x-cut KTP plates with the cutting angles of $\theta = 90^{\circ}$ and $\varphi = 0^{\circ}$. Each plate has a thickness of 1.19 ± 0.01 mm and a cross-section of 5.6 mm×10.5 mm. All 20 pieces are bonded together by AFB technique. Since crystal axes of every other plate are inverted, the signs of nonlinear coupling coefficient d_{eff} are periodically inverted, this periodic alternation the sign of d_{eff} can compensate for the nonzero wave vector mismatch Δk, resulting in the quasi-phase matching (QPM) condition [10,11]. Such a QPM condition causes each pair of the signal and idler in a bulk KTP crystal splitting into two pairs of the orthogonally-polarized signal and idler beams. Therefore, QPM can be used to compensate for the spatial walk-off and allows us to use the largest nonlinear coefficient in the crystal for a nonlinear interaction [10].

Our experimental setup is shown in Fig. 1 for demonstration of image restoration based on broadband and polarization-insensitive phase conjugation. The laser beam (10 Hz repetition, 4.8 ps pulse width) is from an output of Master Oscillator/Power Oscillator (MOPO), with wide range wavelength tenability. The pump beam is split into two parts for each fixed pump wavelength in 535-542 nm. One part is used to pump the optical-parametric oscillator based on a bulk KTP crystal, whereas the other part is directed to the AFB-KTP plates. The idler beam generated from the bulk KTP passes through a cubic polarizer (CP1) and collimated by a pair of convex (L1) and concave (L2) lenses. It then transmits through a phase distortion plate (DP) and used as an input beam for DFG with the green pump beam in the AFB-KTP plates, where temporal and spatial overlaps of the input and pump pulses need to be maintained. Since the DP imposed phase distortion $\varphi(x, y, z)$ on the input signal, the generated phase-conjugate beam from the AFB-KTP plates also has the same phase distortion but with an opposite sign $-\varphi(x, y, z)$. Both the input and generated phase-conjugate beams are reflected back by the high-reflectivity mirror (HR3) and pass through the DP. The input beam suffers the phase distortion of $2\varphi(x, y, z)$ after the second pass of the DP, but for the phase-conjugated beam with the phase distortion of $-\varphi(x, y, z)$, passing through the DP just eliminates the phase distortion and recovers the wave front. Then, the signal and phase conjugate beams are directed to an imaging system by a beam splitter (BS3). The input beam is illuminated on the object and forms a blurring image on the CCD camera because of the phase distortion. While the image formed by the generated phase-conjugate beam will be restored since the phase distortion is removed. The phase conjugate beam has an orthogonal polarization with the input beam. If the input beam is *p*-polarized, it passes through a cubic polarizer (CP2) without reflection, and the generated phase conjugate beam is s-polarized reflecting from the CP2 with an angel ~90°, as shown in Fig. 1. The polarization of the input beam can be tuned by a $\lambda/2$ wave plate. The filter in the imaging arm is used to block the remaining green pump beam. By measuring this phase-conjugated beam, we have corrected the blurred images caused by the distortion plate.

Fig. 2 shows our results of polarization-insensitive restoration of images. The input beam is *p*-polarized for Fig. 2(a) and *s*-polarized for Fig. 2(d) without the phase-distortion plate. After putting in the phase-distortion plate, these images are obviously blurring [Fig. 2(b) and Fig. 2(e)],

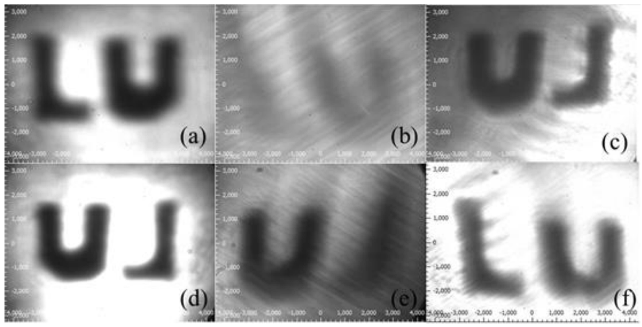

Fig. 2. *P*-polarized (a) and *s*-polarized (d) input beam without distortion images, after distortion images (b) and (e); restored images (c) and (f) by phase-conjugated beams at pump wavelength of 539 nm.

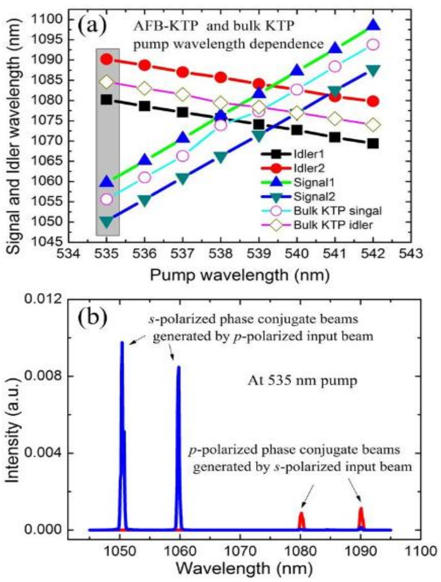

Fig. 3. (Color online) (a) Measured signal and idler wavelengths of AFB-KTP and bulk KTP as a function of pump wavelength; (b) Phase conjugated beam spectra generated by *p*-polarized input beam (blue peaks) and *s*-polarized input beam (red peaks).

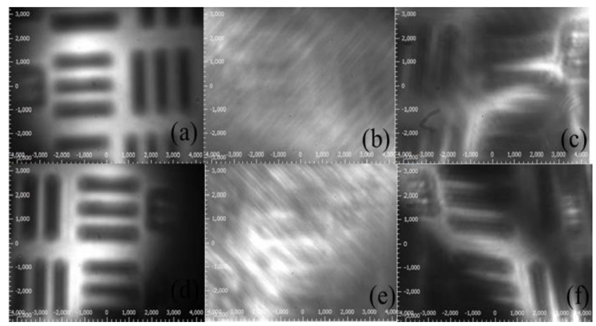

Fig. 4. Image restoration at pump wavelength of 535 nm. *p*-polarized (a) and *s*-polarized (d) input beam without distortion image, after distortion (b) and (e) and restored image (c) and (f) by phase conjugated beams.

since the wave front of the input beam is distorted. The phase-conjugated beam can correct the blurred images, and therefore, restores the images to the original quality [Fig. 2(c) and Fig. 2(f)]. Based on Fig. 2, we have estimated the degree of the image restoration to be 80±20% with 0% and 100% corresponding to no and complete restorations, respectively.

At around 539 nm pump, two pairs of the signal and idler become degenerate, as shown in Fig. 3(a). Therefore, instead of four different wavelengths, there are only two wavelengths of ~1073 nm and ~1083 nm. Each of these two wavelengths contains both *p*- and *s*-polarized components. Therefore, for the input beam wavelength at (or near) these two wavelengths, phase conjugated beams can be always generated for any polarization. Here, using the AFB-TTP crystal, we demonstrate that the imaging restoration based on polarization-insensitive phase conjugation is not only effective at the region of the degenerate pump point, but also in a broad wavelength range (535 -542 nm).

Fig. 4 shows the imaging restoration at 535 nm, i.e. away from the degenerate pump point. In such a case, the blurred images are also restored by the phase conjugated beams for both *p*-polarized and *s*-polarized input beams. Fig. 4(a) and Fig. 4(d) are the original images without the phase-distortion plate for the *p*-polarized and *s*-polarized input beams respectively. These images become blurring after the distortion plate is placed [Fig. 4(b) and Fig. 4(e)], and restored by the phase-conjugate beams [Fig. 4(c) and Fig. 4(f)]. Two pairs of signal and idler will be generated under the 535 nm pump, as seen the gray region in Fig. 3(a). Two idler beams are *p*-polarized and have wavelengths of ~1080 nm and 1090 nm, while the two signal beams are *s*-polarized and have wavelengths of ~1060 nm and 1050 nm. The polarization of the input beam (~1085 nm) can be tuned by the half-wave plate. If the input beam is *p*-polarized, the output phase conjugate beams are *s*-polarized and have exactly the same wavelength as the signal beams generated in the AFB-KTP crystal, as shown in Fig. 3(b) the blue peaks. Rotate the half-wave plate to make the input beam *s*-polarized, and then the phase conjugated beams become *p*-polarized and have exactly the same wavelengths of idler beams as shown by the red peaks in Fig. 3(b). It is worth noting that our experiment is different from the previous work on phase conjugation by DFG [7,9]. In their reports, strict restrains are imposed on polarizations and wavelengths of the input beams – only certain polarization direction and wavelength of the input beams can be used for the generation of phase conjugation beams. In contrast, in our case, phase conjugation beams can be generated by either *p*-polarized or *s*-polarized input beams, i.e. it can be generated by the input beam at any polarization direction. Also, this polarization-insensitive phase conjugation can be achieved at broad wavelength range (535 - 542 nm), besides the wavelength at the degenerate pump point (~539 nm). One limitation of our method is that two phase-conjugate wavelengths generated propagate with a very small angle. Therefore, the propagating distance of the phase-conjugate beams needs to be kept as short as possible, before they are divided into two separate beams and illuminate the object and camera.

In conclusion, imaging restoration based on phase conjugation has been achieved by a three-wave interaction process in the AFB-KTP nonlinear crystal. A second-order nonlinear coefficient instead of a third-order nonlinear coefficient is used in the parametric process. Due to the satisfaction of QPM in the AFB crystal, broadband and polarization-insensitive phase conjugation is realized in our experiment, which could have important applications in maintaining and improving the resolutions of images. In principle, passive imaging can be realized based on our scheme by sacrificing sensitivities.

References to Section 2

1. Z. Yaqoob, D. Psaltis, M. S. Feld, and C. H. Yang, Nat. Photonics **2**, 110 (2008).
2. J. Khoury, J. S. Kane, P. D. Gianino, P. L. Hemmer, and C. L. Woods, Opt. Lett. **26**, 1433 (2001).
3. I. M. Vellekoop, M. Cui, and C. H. Yang, Appl. Phys. Lett. **101**, 081108 (2012).
4. R. A. Fisher, ed., *Optical phase conjugation*, Academic, NY, 1983.
5. G. S. He, Prog. Quantum Electron. **26**, 131 (2002).
6. Y. J. Ding, Opt. Lett. **37**, 4792 (2012).
7. F. Devaux, E. Guiot, and E. Lantz, Opt. Lett. **23**, 1597 (1998).
8. F. Devaux, G. le Tolguenec, and E. Lantz, Opt. Commun. **147**, 309 (1998).
9. L. Lefort and A. Barthelemy, Opt. Lett. **21**, 848 (1996).
10. X. D. Mu, H. Meissner, and H. C. Lee, Opt. Lett. **35**, 387 (2010).
11. P. Zhao, S. Ragam, Y. J. Ding, I. B. Zotova, X. D. Mu, H. C. Lee, S. K. Meissner, and H. Meissner, Opt. Lett. **37**, 1283 (2012).
12. V. N. Mikhailov, M. Bondani, F. Paleari, and A. Andreoni, J. Opt. Soc. Am. B: Opt. Phys. **20**, 1715 (2003).
13. V. I. Sokolov, A. M. Nugumanov, and R. V. Smirnov, Opt. Commun. **189**, 377 (2001).
14. Y. J. Ding, J. B. Khurgin, and S. J. Lee, Opt. Quantum Electron. **28**, 1617 (1996).
15. Y. J. Ding and J. B. Khurgin, J. Opt. Soc. Amer. B **14**, 2161 (1997).

3. Phase conjugation based on single backward second-order nonlinear parametric process

We have shown that backward difference-frequency generation can be exploited to achieve phase conjugation in a second-order nonlinear medium. The backward configuration can be utilized to achieve broadband quasi-phasematching, compared with the forward counterpart. Our calculation shows that a nonlinear reflectivity of close to 100% is achievable from a laser emitting an output power of ≈ 1 mW. Such an efficient phase conjugator is made feasible by placing the nonlinear medium inside a pump laser cavity. In addition, a Fabry-Perot cavity at the input frequency is used to significantly improve the nonlinear reflectivity.

Our theory has been confirmed in our experiments, see Sections 1 and 2 above.

Phase conjugation can be used to correct blurred images caused by atmospheric turbulence. In the past, phase-conjugation devices based on photorefractive effect have response times in the range of 100 μs – 1 s [1], i.e. they are extremely slow. Obviously, such response times make the corresponding scheme impracticable for compensating the blurred images due to atmospheric turbulence. It is well known that four-wave mixing in a third-order nonlinear medium can be also used to achieve optical phase conjugation [2]. This scheme, demonstrated in Ref. [3], requires two pump beams. What is more, since third-order nonlinearity is weak, the pump powers must be extremely high in order to achieve a reasonably high nonlinear power reflection coefficient, i.e. nonlinear reflectivity (e.g. $R_{pc} \geq 1\%$). Therefore, it is still questionable whether such a scheme is practical for restoring the images distorted by atmospheric turbulence. We would like to note that the advantage of four-wave mixing over photorefractive effect lies in the fact that the response time is limited only by the temporal resolution of imaging devices. Besides third-order nonlinearities, phase conjugation was theoretically investigated by utilizing cascaded second-order nonlinear-optical processes, which is equivalent to effective third-order nonlinear processes, in a transverse-pumping geometry [4]. By replacing the second-harmonic beam with a pump beam, spectral phase conjugation is feasible [5].

Here, we report our theoretical result showing that a single second-order nonlinear process can be exploited to achieve phase conjugation. Our calculation indicates that a reflection coefficient of close to 100% is achievable at the pump power available from a low-power CW laser. Moreover, large gains can be obtained, as the pump power is increased. All these powers are much lower than that for reaching backward optical parametric oscillation [6,7]. Our scheme is unique. First, the backward configuration allows us to achieve broadband quasi-phasematching. Second, the intracavity scheme leads to the significant reduction in the pump intensity. Third, the Fabry-Perot cavity for the input signal significantly improves the nonlinear reflectivity. Compared with phase conjugation based on four-wave mixing [2], our scheme requires much lower pump powers to achieve the nonlinear reflectivity of 100%.

Fig. 1 illustrates the wave-propagation configuration for phase conjugation. A second-order nonlinear medium is placed inside a pump laser cavity oscillating at ω_p. Due to the presence of two counter-propagating pump beams inside the laser cavity, two configurations, as shown by Figs. 2(a) and 2(b), can be quasi-phasematched according to the following condition:

$$k_p - k_i + k_{pc} = \frac{2\pi}{\Lambda} \tag{1}$$

where $n_{p,i,pc}$ are indices of refraction for the pump, input, and phase-conjugate waves, respectively, $k_{p,i,pc} = 2\pi n_{p,i,pc}/\lambda_{p,i,pc}$ are the corresponding wave vectors with $\lambda_{p,i,pc}$ being the corresponding wavelengths, and Λ is the poling period. Consider a nearly degenerate backward difference-frequency generation for realizing phase conjugation, i.e. $\lambda_{pc} \approx \lambda_i$. We assume that the spatial depletion for the counter-propagating pump waves is insignificant.

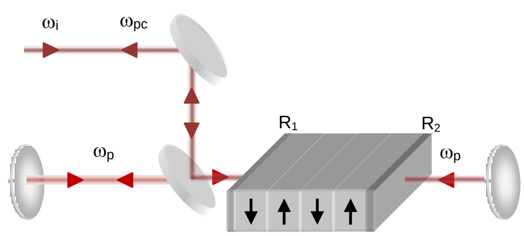

Fig. 1. Configuration proposed for achieving phase conjugation.

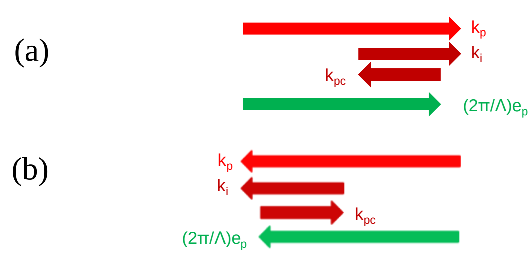

Fig. 2. (a) and (b) Backward quasi-phasematching diagrams in terms of wave vectors. These wave vectors satisfy Eq. (1), since each wave vector in (b) switches its direction relative to that in (a).

Using Maxwell's equations [8], we have obtained the following coupled wave equations when the quasi-phasematching condition, Eq. (1), is satisfied:

$$\frac{dA_i^{\pm}}{dz} = \pm i\Gamma (A_{pc}^{\mp})^* A_p^{\pm} \tag{2}$$

$$\frac{dA_{pc}^{\pm}}{dz} = \pm i\Gamma (A_i^{\mp})^* A_p^{\mp} \tag{3}$$

where A_i, A_{pc}, and A_p are the electric-field amplitudes of the input, phase-conjugate, and pump waves, respectively, ± in the subscripts designate forward and backward propagation directions, and $\Gamma = 2\pi d_{eff}^{(2)} / \sqrt{\lambda_i \lambda_{pc} n_i n_{pc}}$ is the nonlinear coupling strength between the input and phase-conjugate waves with $d_{eff}^{(2)}$ being the effective second-order nonlinear coefficient for the parametric interaction. We neglect the Fabry-Perot effect at λ_{pc} such that the following boundary conditions are satisfied:

$$A_{pc}^{+}(0) = A_{pc}^{-}(L) = 0 \tag{4}$$

where L is the length of the nonlinear medium. For the amplitude of the input beam entering the Fabry-Perot resonator to be A_{i0}, we impose the following boundary condition:

$$A_i^{+}(0) = A_{i0} + \sqrt{R_1} A_i^{-}(0) \tag{5}$$

where R_1 is the reflectivity of the left mirror forming the Fabry-Perot resonator at λ_i in Fig. 1. After solving Eqs. (2) and (3) under the boundary conditions, i.e. Eqs. (4) and (5), we have obtained the amplitude of the backward-propagating wave to be:

$$A_{pc}^{-}(0) = i \exp(i\varphi_p^{+}) \frac{\sqrt{\hat{I}_p}}{(1-\hat{I}_p)\sqrt{1-R}} A_{i0}^* \tag{6}$$

where $R = R_1 = R_2$ is the reflectivity of each mirror used to form the Fabry-Perot resonator at λ_i, φ_p^{+} is the phase of the electric field of the forward-propagating pump beam inside the laser cavity, and $\hat{I}_p$ is the pump intensity of the forwarding-propagating beam, normalized by the threshold for reaching the backward optical parametric oscillation, defined as [6]:

$$I_{th} = \frac{\lambda_i \lambda_{pc} n_i n_{pc} n_p (1-R) m^2}{32 \eta_0 d_{33}^2 L^2} \tag{7}$$

where m is the order of the periodically-poled nonlinear grating used for achieving quasi-phasematching and d_{33} is the nonlinear coefficient used for the parametric interaction. Due to the parametric conversion, for the reflectivities of the resonator, given by $R_1 = R_2 e^{2gL}$, where g is the parametric gain coefficient, the back-propagating wave at λ_i outside the resonator is eliminated

[9]. Consequently, there is only one backward-propagating wave at λ_{pc}. According to Eq. (6), this wave is indeed the phase conjugate of the input wave, in the presence of the resonator.

Based on Eq. (6), the nonlinear reflectivity is

$$R_{pc} = \frac{\hat{I}_p}{(\hat{I}_p - 1)^2 (1 - R)} \tag{8}$$

One can see from Eqs. (7) and (8) that for the nearly- degenerate configuration the resonator is used to reduce the pump intensity required and to enhance the nonlinear reflectivity. According to Eq. (8), even if the pump intensity is much lower than the threshold for the backward oscillation, i.e., $\hat{I}_p \ll 1$, the nonlinear reflectivity can be quite high, provided if the reflectivity for each of the two mirrors forming the Fabry-Perot resonator is sufficiently high. Indeed, one can see from Eq. (8) that if $\hat{I}_p = 1 - R$, $R_{pc} = 1/R^2$., which is slightly larger than 100%, i.e. there is a slight gain for the phase conjugation. Based on Eq. (8), R_{pc} = 100%, if $\hat{I}_p = (1-R)/(3-2R)$, which is slightly lower than 1-R if $R \approx$ 100%.

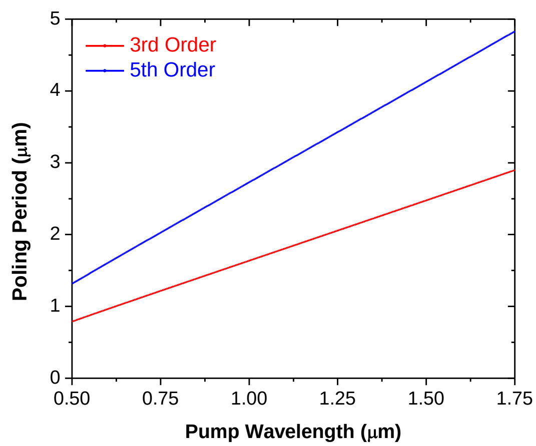

Fig. 3. Poling period vs. pump wavelength based on 3rd and 5th orders of the nonlinear grating in periodically-poled KTP.

Using Eq. (1), we have calculated the poling period as a function of the pump wavelength at the 3rd and 5th orders of the nonlinear grating for the periodically-poled $KTiOPO_4$ (KTP), see Fig. 3. According to Refs. [7,10], these periods can be fabricated on KTP wafers. One of the advantages for phase conjugation based on the backward parametric process lies in the fact that the phase-matching bandwidth can be significantly broadened. Indeed, in our recent study [11], we demonstrated that the phase-matching bandwidth was increased by a factor of 33, when the poling period for KTP is 2.55 μm. Such an increase is due to the fluctuation in the poling period from one period to the next. By controlling linear tapering on the period, we can further broadening the phase-matching bandwidth.

On the other hand, the corresponding poling periods for $LiNbO_3$ are too short such that it would be difficult to fabricate the high-quality periodically-inverted domains having large cross-sectional dimensions. One possible solution is to take advantage of surface poling [12]. In such a case, phase conjugation can be realized in a waveguide consisting of periodically-poled $LiNbO_3$. Although one can exploit a forward configuration to realize phase conjugation in periodically-poled KTP, the phase-matching bandwidth is narrow [9]. It can be broadened, if a series of KTP crystals are aperiodically inverted following the work [13].

Based on Eq. (8), we have calculated the nonlinear reflectivity. According to Fig. 4, the nonlinear reflectivity, R_{pc}, reaches 100% when $I_p \approx 0.001\ I_{th}$, i.e. much below I_{th}. Consider a periodically-poled KTP crystal: $\Lambda \approx 2.91$ μm, $R \approx 99.9\%$, and $L \approx 5$ mm. I_p for $R_{pc} \approx 100\%$ at $\lambda_i \approx 2$ μm is estimated to be 738 W/cm^2 at 1 μm. Such an intensity is translated into an intracavity power of 22 mW, corresponding to an output power of 1 mW from a low-power CW laser. Therefore, the proposed phase-conjugate mirror requires a much lower pump power compared with that based on the four-wave mixing. Moreover, such a pump level is comparable with that based on the photorefractive effect. However, our scheme is just limited by the laser cavity lifetime in terms of the response times, unlike that based on the photorefractive effect. When the pump power is above 22 mW, $R_{pc} > 1$, i.e. there is a gain, see Fig. 4. For example, when the intracavity pump power reaches 1.8 W, R_{pc} reaches 100. As I_p approaches I_{th}, R_{pc} approaches ∞, i.e. backward optical parametric oscillation takes place. These behaviors are similar to those based on four-wave mixing [8].

In conclusion, we have showed that phase conjugation based on backward second-order nonlinear parametric interaction can be efficient. Indeed, our result indicates that pump powers of as low as 1 mW are sufficient to reach the nonlinear reflectivity of close to 100%. This is due to the intracavity parametric process and Fabry-Perot resonator. Based on our previous result, the backward parametric process has its own advantage of significantly broadening the phase-matching bandwidth. Compared with phase conjugation based on photorefractive effect, our scheme is only limited by the laser cavity lifetime. Our scheme has a major advantage over that based on four-wave mixing, i.e. much lower pump powers are required to reach the nonlinear reflectivity of 100%.

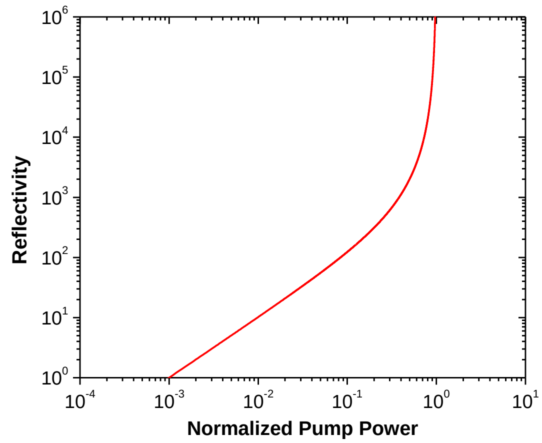

Fig. 4. Nonlinear reflectivity for phase conjugation vs. pump power normalized by threshold for backward optical parametric oscillation, given by Eq. (7).

References to Section 3

1. P. Yeh, Appl. Opt. **26**, 602 (1987).
2. For a review, see various chapters in R. A. Fisher, ed., *Optical phase conjugation*, Academic, NY, 1983.
3. M. V. Vasil´ev, V. Yu. Venediktov, and A. A. Leshchev, "Quantum Electron. **31**, 1 (2001).
4. Y. J. Ding, J. B. Khurgin, and S. J. Lee, Opt. Quantum Electron. **28**, 1617 (1996).
5. M. Tsang and D. Psaltis, Opt. Commun. **242**, 659 (2004).
6. Y. J. Ding and J. B. Khurgin, IEEE J. Quant. Electron. **32**, 1574 (1996).
7. C. Canalias and V. Pasiskevicius, Nature Photon. **1**, 459 (2007).
8. A. Yariv, *Quantum electronics*, Wiley, NY, 1989, pp. 435-437; pp. 498-506.
9. L. A. Coldren and S. W. Corzine, *Diode lasers and photonic circuits*, Wiley, NY, 1995, p. 77.
10. B. Zhang, Y. J. Ding, and I. B. Zotova, Appl. Phys. B **99**, 629 (2010).
11. Y. Jiang, D. Li, Y. J. Ding, and I. B. Zotova, "Broadband Phase-Matched Backward Difference-Frequency Generation: A Novel Scheme for Spectral Optical Phase Conjugation," CLEO 2011, May 1-6, Baltimore, MD, JThB92.
12. S. Stivala, A. Pasquazi, L. Colace, G. Assanto, A. C. Busacca, M. Cherchi, S. Riva-Sanseverino, A. C. Cino, and A. Parisi, J. Opt. Soc. Amer. B **24**, 1564 (2007).
13. X. D. Mu, H. Meissner, and H. C. Lee, Opt. Lett. **35**, 387 (2010).

Personnel Supported

Yujie J. Ding
Pu Zhao
Xiaomu Lin
Pengda Hong
Zhaojun Liu
Xingquan Zou

Publications

1. X. Zou, P. Zhao, P. Hong, X. Lin, Y. J. Ding, X. Mu, H.-C. Lee, S. K. Meissner, and H. Meissner, "Restoration of Blurred Images Due to Phase Distortion Based on Polarization-Insensitive Phase Conjugation in Second-Order Nonlinear Medium," Opt. Lett., vol. 38, no. 16, Aug. 15, 2013, pp. 3054-3056.
2. Y. J. Ding, "Phase conjugation based on single backward second-order nonlinear parametric process," Opt. Lett., vol. 37, no. 22, Nov. 15, 2012, pp. 4792-4794.

Interactions/Transitions

1. Y. J. Ding, "Correction of Blurred Image by Exploiting Phase Conjugation Based on Single Second-Order Nonlinear Parametric Processes," SPIE Optical Engineering + Applications, Aug. 25-29, 2013, San Diego, CA. (**Invited**).
2. P. Zhao, Z. Liu, X. Lin, Y. J. Ding, X. Mu, H.-C. Lee, S. K. Meissner, and H. Meissner, "Polarization-Insensitive Optical Phase Conjugation Based on Adhesive-Free-Bonded Periodically-Inverted $KTiOPO_4$ Plates," CLEO 2013, CTu3E.7 (**Refereed**).
3. X. Zou, X. Lin, P. Zhao, P. Hong, Y. J. Ding, X. Mu, H.-C. Lee, S. Meissner, and H. Meissner, "Restoration of blurred images due to phase distortion based on polarization-insensitive phase conjugation in second-order nonlinear medium: novel scheme," CLEO 2013, QM4E.5 (**Refereed**).
4. Y. J. Ding, "Instantaneous phase conjugation ay mW pump power based on backward difference-frequency generation," IPC 2012, San Francisco, CA, Paper WB3 (**Refereed**).
5. Y. J. Ding, "Phase conjugation based on backward difference-frequency generation: a novel scheme," CLEO 2012, QF2G.2 (**Refereed**).

New discoveries, inventions, or patent disclosures

New discoveries

- For the first time, we have demonstrated the restoration of blurred images caused by phase distortion. This result will be the first step for us to improve the sensitivities and resolutions for imaging and communications through atmosphere.

Inventions or patent disclosures

- None.

Honors/Awards

- OSA Fellow.
- IEEE Fellow.